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NOTE ON ANTINEUTRINO CROSS SECTIONS
AND ON DETECTION OF ANTINEUTRINOS
FROM NUCLEAR EXPLOSIONS

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SUMMARY

Cross sections for various antineutrino reactions are estimated. Based on these estimates it is concluded that no antineutrino reactions are useful as a basis for detecting nuclear explosions at great distances.

NOTE ON ANTINEUTRINO CROSS SECTIONS
AND ON DETECTION OF ANTINEUTRINOS
FROM NUCLEAR EXPLOSIONS

The fission products from a nuclear explosion provide a strong source of antineutrinos which some people have suggested could be used for detecting nuclear explosions. Antineutrinos have the advantage for detection that they are produced by all nuclear explosions, even decoupled ones. They have the disadvantage that they interact extremely weakly with matter and consequently their detection is difficult.

The only known means for detecting antineutrinos are based upon observing one of the following reactions:

- | | |
|---|------------------------------------|
| (a) $\bar{\nu} + P \longrightarrow N + \beta^+$ | Inverse β Decay, |
| (b) $\bar{\nu} + e \longrightarrow \bar{\nu} + e$ | Scattering, |
| (c) $\bar{\nu} + \text{Nucleon} \longrightarrow \bar{\nu} + \text{Nucleon}$ | Scattering (Elastic or Inelastic). |

Reaction (a) has been observed by Reines and Cowan¹ to have a cross section $\sigma_{RC} = 10^{-43} \text{ cm}^2$ at fission antineutrino energies. The magnitudes of the other cross sections are unknown.

Detection of Nuclear Explosions

At a distance of R kilometers from a nuclear explosion with fission yield Y kilotons, the total number of antineutrinos per cm^2 from beta decay

¹F. Reines and C. L. Cowan, Jr., Phys. Rev. 113, 273 (1959).

of fission products is

$$\frac{Y}{R} \times 10^{12} \text{ antineutrinos/cm}^2.$$

Nearly all the fission-product antineutrinos are produced within the first few seconds after the explosion.

For a detector containing N target particles, the expected number of antineutrino reactions of cross section σ is

$$\frac{N\sigma Y}{R} \times 10^{12}.$$

Observation of these reactions is in general limited by extraneous backgrounds. However, for detecting nuclear explosions we shall make the extreme assumption that there are no extraneous backgrounds. In this case detection is limited by the probability that a single reaction is observed. If it is required for detection that at least one reaction is observed with a probability of .95, then on the average 3 reactions produced by the explosion must be observed, or

$$\frac{N\sigma Y}{R} \times 10^{12} = 3.$$

The maximum detection range of a nuclear explosion of fission yield Y kilotons would then be

$$R = 1.8 \times 10^{-16} \sqrt{\frac{\sigma}{\sigma_{RC}}} NY \text{ km.}$$

For an explicit estimate of the feasible detection ranges of anti-neutrinos from nuclear explosions it will be assumed that a detector similar to that used by Reines and Cowan for the measurement of reaction (a) is used. This detector consisted of 400 liters of water (containing a small amount of cadmium salt) as the target, and 5400 liters of liquid scintillator material to observe triple coincidences among the pair-annihilation γ rays and the neutron-capture γ ray. The target contained 10^{29} protons. The total weight of target and scintillator liquids (i. e., excluding walls, electronics, shielding, etc.) was about 6 tons. For this detector, where it is assumed that antineutrino reactions are observed with 100 per cent efficiency and that there are no extraneous backgrounds, the maximum detection range would be

$$R = 5.8 \times 10^{-2} \sqrt{Y} \sqrt{\frac{\sigma}{\sigma_{RC}}} \text{ km} \approx 60 \sqrt{Y} \sqrt{\frac{\sigma}{\sigma_{RC}}} \text{ meters.}$$

Even if 1000 Reines-Cowan-type detectors ($N = 10^{32}$, about 6000 tons of scintillator material) were used, where again the extreme assumption of no extraneous backgrounds is made and if it is assumed that the detection efficiency is 100 per cent, the maximum detection range would be

$$R = 1.8 \sqrt{Y} \sqrt{\frac{\sigma}{\sigma_{RC}}} \text{ km,}$$

and a 100-kiloton bomb, under ideal conditions, would be observed by reaction (a) with 95 per cent probability at only 18 kilometers.²

²See also R. O. Hundley, The RAND Corporation, Research Memorandum RM-2641.

Obviously, only if reactions (b) and (c) had cross sections many orders of magnitude larger than reaction (a) is there any hope of using antineutrinos for detection purposes. However, even if reactions (b) and (c) had larger cross sections, they probably would still be less useful than reaction (a), since reaction (a) leads to simultaneous emission of three γ rays. And a triple coincidence of γ rays can effectively suppress backgrounds — unlike the non-unique products of reactions (b) and (c).

For the remainder of this note the evidence on the magnitudes of the cross sections for reactions (b) and (c) is discussed.

$(\bar{\nu}, e)$ -Scattering Cross Section

If the coupling of antineutrinos and electrons is the same as in ordinary beta decay, then theoretically the $(\bar{\nu}, e)$ -scattering cross section³ would be (for 3 Mev antineutrinos) $\sim 10^{-44} \text{ cm}^2$, that is, somewhat smaller than the cross section of reaction (a).

It is possible, however, that a different $(\bar{\nu}, e)$ -coupling exists with an as yet unknown coupling constant. Thus to estimate the magnitude of the $(\bar{\nu}, e)$ -cross section experimental data are needed. Such data exist.

Using the same scintillation detectors which they used for measuring the cross section of reaction (a), Reines and Cowan measured the "singles" counting rate from reactor antineutrinos. If the entire "singles" counting

³R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

rate which they observed is ascribed to electrons scattered by antineutrinos (reaction (b)), an upper limit on the $(\bar{\nu}, e)$ -scattering cross section can be determined. Reines and Cowan's⁴ first experiments gave an upper limit of $\sim 10^{-39} \text{ cm}^2$. Reines and Cowan interpreted this cross section in terms of an upper limit of 10^{-7} Bohr magnetons for the antineutrino magnetic moment. Later experiments⁵ by Reines and Cowan using larger detectors gave an upper limit of 10^{-9} Bohr magnetons for the magnetic moment of the antineutrino. This magnetic moment is equivalent to an upper limit of 10^{-43} cm^2 for the fission antineutrino-electron scattering cross section.

Thus, the detection range of nuclear explosions using the $(\bar{\nu}, e)$ -scattering process (reaction (b)) is no greater than using inverse beta decay (reaction (a)). Moreover, using the $(\bar{\nu}, e)$ -scattering process has the disadvantage that the reaction products are not unique to the specific antineutrino reaction.

$(\bar{\nu}, \text{nucleon})$ -Scattering

In the absence of a direct $(\bar{\nu}, \text{nucleon})$ -interaction, $(\bar{\nu}, \text{nucleon})$ -scattering can theoretically still occur by means of an electromagnetic interaction between a nucleon and a virtual electron pair coupled to an antineutrino. A theoretical estimate of the cross section of this process is $(e^2/\hbar c)^2 \approx 10^{-4}$ times the $(\bar{\nu}, e)$ -cross section, or less than $\sim 10^{-47} \text{ cm}^2$.

⁴C. L. Cowan, Jr., F. Reines, and F. B. Harrison, Phys. Rev. **96**, 1294 (1954).

⁵F. Reines and C. L. Cowan, Jr., Nature, **178**, 446 (1956).

However, it is possible that a direct ($\bar{\nu}$, nucleon)-interaction exists, and therefore experimental data are required in order to determine the cross section of this process.

Direct experimental information on the ($\bar{\nu}$, nucleon)-elastic scattering cross section is available. The high energy accelerator at CERN produces Bev- π mesons which, when they decay, produce along with μ mesons an intense neutrino and antineutrino beam with an energy ~ 1 Bev. Using this beam, preliminary measurements have been made which put a definite upper limit of 10^{-36} cm^2 , and a possible upper limit of 10^{-37} cm^2 , on the ($\bar{\nu}$, nucleon)-cross section at 1 Bev.⁶ Unfortunately, to apply this result to the detection problem requires extrapolation of the measured cross section to energies of Mev's. This extrapolation must be based on theory and therefore could be wrong. Nonetheless, theoretically, the most general form for the ($\bar{\nu}$, nucleon)-scattering cross section (consistent with present knowledge about neutrinos) is

$$\sigma_{(\bar{\nu}, N)} = \frac{2}{\pi} \left\{ G_1^2 \left(\frac{E_\nu}{M} \right)^2 \left(1 + \frac{2E_\nu}{M} \right)^{-1} + \frac{1}{6} G_2^2 \left(\frac{E_\nu}{M} \right)^2 \left[1 - \left(1 + \frac{2E_\nu}{M} \right)^{-3} \right] - G_1 G_2 \left(\frac{E_\nu}{M} \right)^2 \left(1 + \frac{2E_\nu}{M} \right)^{-2} \right\},$$

where E_ν is the antineutrino energy and M is the nucleon rest energy

⁶S. Berman, private communication.

(~ 1 Bev). G_1 and G_2 are (unknown) coupling constants which determine the mixture of vector and axial vector couplings for the nucleon. Choosing the ratio of G_1 to G_2 so as to make the low energy cross section as large as possible, the cross section (using 10^{-36} cm² as the upper limit at 1 Bev) is

$$\sigma_{(\bar{\nu}, N)} < 4(E_{\nu})^2 \times 10^{-42} \text{ cm}^2,$$

where E_{ν} is measured in Mev. Thus for fission antineutrinos ($E_{\nu} \sim 3$ Mev), the $(\bar{\nu}, \text{nucleon})$ -elastic scattering cross section is theoretically less than $\sim 4 \times 10^{-41}$ cm².

For detection of elastic scattering it should be noted, however, that detectors are very inefficient for counting the low energy (few kilovolt) recoil protons arising from fission antineutrinos. Such low energy protons are equivalent in ionizing power only to electron volt electrons. Thus, if only elastic scattering of nucleons occurs, then antineutrinos would not be useful for detecting nuclear explosions.

So far as inelastic scattering is concerned, the $(\bar{\nu}, \text{nucleon})$ -cross section measured at CERN is an upper bound since any scattering process requiring a threshold has a smaller cross section than that corresponding to complete elastic scattering. Nuclear matrix elements imply a further reduction in the inelastic scattering cross section compared to the cross section measured at CERN. The CERN experiments therefore only lead to a reasonable theoretical upper limit on the $(\bar{\nu}, \text{nucleon})$ -inelastic scattering

cross section at fission energies.

More direct information on the actual inelastic scattering cross section is provided by the Reines-Cowan measurements.⁴ In these measurements, if a ($\bar{\nu}$, nucleon)-interaction gave rise to an inelastic scattering which left an excited nucleus, then the decay gamma rays (in the Mev range) could have been efficiently detected by the liquid scintillators. To overestimate the cross section for the ($\bar{\nu}$, nucleon)-inelastic scattering it will be assumed that the "singles" counting rate observed by Reines and Cowan was due entirely to the ($\bar{\nu}$, nucleon)-inelastic scattering.

The Reines-Cowan scintillator material was composed mostly of carbon and hydrogen, with small parts of nitrogen, oxygen, and phosphorus. The first excited level in carbon is at 4.4 Mev, so fission antineutrinos are energetically able to have excited this level. In addition, there were in the walls, earth, etc., surrounding the scintillator other nuclei, such as silicon, aluminum, lead, and iron, which could have been excited by fission antineutrinos. The mean free path for γ rays of a few Mev is about 40 g/cm²; thus the detector of 1400 liters could efficiently have detected gamma rays from about 3×10^6 grams of target, that is, about 2×10^{30} nucleons, or a few times the number of target particles in the scintillator itself. The actual detection efficiency of Mev-gamma rays was perhaps one-third to one-half. If all the Reines-Cowan background counts are ascribed to the excitation of some particular element in or near the scintillator, the ($\bar{\nu}$, nucleon)-inelastic scattering cross section

would be less than a few times 10^{-43} cm^2 .

A possibility which cannot entirely be ruled out is that the "singles" counts measured by Reines and Cowan were in fact due to a nuclear excitation of an element present only in very small amounts. This could lead to a large cross section for that particular interaction. This appears to be an entirely unreasonable interpretation since it requires that reaction (c) be forbidden for all those elements which were present in appreciable amounts in or near the scintillator.

Discussion

Even in the absence of backgrounds, the detection range of reaction (b) appears to be the same as for reaction (a) and the range of reaction (c), less than a few times that for reaction (a). However, products of reactions (b) and (c) are not unique to antineutrino reactions. Backgrounds are probably large. This additional complication probably makes reactions (b) and (c) even less useful than the (impractical) reaction (a).

In summary, the cross sections of reactions (a), (b), and (c) at fission antineutrino energies are

- (i) $\sigma \text{ (reaction (a))} \sim 10^{-43} \text{ cm}^2$,
- (ii) $\sigma \text{ (reaction (b))} \lesssim 10^{-43} \text{ cm}^2$,
- (iii) $\sigma \text{ (reaction (c), inelastic)} \lesssim \text{few} \times 10^{-43} \text{ cm}^2$, for a wide variety of nuclei,

- (iv) σ (reaction (c), elastic) $\lesssim 4 \times 10^{-41} \text{ cm}^2$, based on theoretical extrapolation from 1 Bev, but probably not observable for fission antineutrinos.

The maximum detection range for antineutrinos is small and this method of detecting nuclear explosions is apparently not useful.

Acknowledgment

We wish to thank Mr. S. Coleman for calculating the theoretical cross section of $(\bar{\nu}, \text{nucleon})$ -scattering.